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A NUMERICAL ANALYSIS OF THE EFFECT OF MESH SENSITIVITY
ON BALLISTIC LIMIT PREDICTION

by

D. Nandlall
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December / décembre 1998

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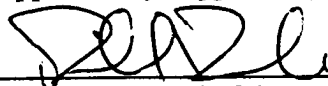
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ABSTRACT

This memorandum presents a study to examine the effect of the mesh density on the ballistic limit determination of a 1.08-cm thick 6061-T6 aluminium plate struck by a 5.56-mm SS109 bullet.

The ballistic limits of the target plate were obtained for three different mesh densities. The results showed that an optimised finite element mesh in the impact region would yield consistent penetration results. It was also shown that as the number of elements is increased, the CPU run time increases significantly but with little gain in the accuracy of the ballistic limit. On the other hand, if the number of elements is decreased below the optimised mesh density, the CPU time could increase significantly and errors in the accuracy of the predicted ballistic limit could be large due to hourglassing and severe mesh distortion.

RÉSUMÉ

Ce mémorandum décrit une étude effectuée pour examiner l'effet de la densité du maillage sur la détermination de la limite balistique d'une plaque d'aluminium 6061-T6 d'une épaisseur de 10,8 mm frappée par un projectile SS109 de 5,56 mm.

Les limites balistiques de la cible ont été obtenues pour trois densités de maillage différentes. Les résultats obtenus ont montré qu'un maillage de l'élément fini optimisé dans la zone d'impact est nécessaire pour obtenir des résultats de pénétration consistants. Il a de plus démontré que lorsqu'on augmente le nombre d'élément le temps de calcul augmente considérablement sans améliorer la précision des résultats. On a également constaté que, si le nombre d'éléments est inférieur à la densité de maillage optimal, le temps de calcul peut aussi augmenter considérablement. Par conséquent, l'imprécision de la limite balistique peut s'accroître en raison des déformations sévères du maillage.

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FIGURES 1 to 8

TABLES I to III

EXECUTIVE SUMMARY

A large number of threats faced by vehicle and personnel today can achieve very high velocities and hence achieve higher lethality levels. To counter these threats, personnel and vehicle armour systems are becoming more and more complex, especially with the proliferation of composites and other new and exotic materials in the defence industry. To better understand the transient deformation, penetration and subsequent perforation of materials, the Defence Research Establishment Valcartier has been conducting experiments to evaluate the ballistic performance of these materials. However, many significant phenomena appear to be experimentally intractable and numerical simulations are required to fully understand the phenomena involved. In recent years, hydrocode simulations have proven to be a useful tool for solving design problems related to armour systems. Due to the complexity of material deformation at high strain rates, hydrocode simulations involving penetration mechanics can be difficult to perform mainly because of the large deformations experienced by the finite element mesh. In general, very good agreement between hydrocode modelling, experiments and theory can be obtained. Great care is however required in the definition of the problem from the numerical and material modelling standpoints. Defining an adequate finite element mesh is an important aspect of conducting successful hydrocode simulations.

In this study, an attempt is made to examine the effect of the finite element mesh density on the prediction of the ballistic limit of a 10.8-mm thick 6061-T6 aluminium plate struck by a 5.56-mm SS109 bullet. Simulations were performed on three different mesh densities and the results obtained show that an optimised finite element mesh in the impact region will yield consistent penetration results with a minimum run time.

The results of this study will improve DND's numerical prediction capabilities and help guide experimental studies at DREV, particularly given the large amount of resources involved when terminal ballistics experiments are required.

1.0 INTRODUCTION

In armour design the extent to which projectiles travelling at high velocity are able to penetrate armour systems of various compositions and thicknesses is obviously an important consideration. When both projectile and target materials are deforming hydrodynamically, the penetration problem becomes extremely complex to analyse either analytically or experimentally. This complexity is ---mainly due to the interaction of the dynamic properties of two materials. As a result approximate solutions are usually all that can be obtained.

In recent years, hydrocode simulations have proven to be a useful tool for solving the design problems that involve the complexities of penetration mechanics just described. These hydrocodes are large computer programs that can be used to numerically simulate highly dynamic events, particularly those involving shocks, by approximating a continuum in a pointwise (finite difference) or piecewise (finite element) manner, and then solving the conservative equations coupled with material descriptions. However, to date computational modelling of failure in hydrocodes has been essentially limited to only a single model of failure. In a recent study (Ref. 1) on the effect of nonlocal damage treatment of dynamic fracture predictions, it was shown that the numerical predictions of fracture exhibit a strong mesh sensitivity. However, an erosion algorithm is needed to simulate actual penetration of the target or erosion of the penetrator. In this context, erosion is basically characterised by total material failure (for example powdering) of a particular element. As described by Anderson and Bodner (Ref. 2) from a numerical viewpoint, total failure occurs when the equivalent strain exceeds a user prescribed erosion strain. This erosion strain depends to a large extent on the size of the mesh used to discretize the continuum. This aspect of erosion strain leads one to suspect that optimising the mesh density could lead to more accurate results at minimum CPU costs.

The work presented in this memorandum examines the effect of mesh density on the ballistic limit of a 10.8-mm thick 6061-T6 aluminum plate struck by a 5.56-mm SS109 bullet. This work was performed at DREV between May and August, 1998 under Thrust 2fe23, Ballistic Protection and Survivability, Numerical Modelling of Ballistics Events.

2.0 OBJECTIVES

The primary objective of this work is to use numerical simulations to investigate the variation in the predicted ballistic limit of a 10.8-mm thick, 6061-T6 aluminum plate as a function of the mesh density used in the numerical simulations. The effect of a non-optimised density on the required CPU time to perform the calculation and the accuracy of the results is also examined.

3.0 NUMERICAL SIMULATIONS

LS-DYNA2D (Ref. 3) is a hydrodynamic finite element computer code. It was used to simulate the impact of a 5.56-mm SS109 bullet on a 10.8-mm thick, aluminum plate in order to determine the ballistic limit. The LS-DYNA2D hydrocode is an explicit two dimensional lagrangian finite element code used for analysing the large deformation and high strain rate response of inelastic structures.

3.1 Projectile and Target Description

Figure 1 shows the main features of the 5.56-mm SS109 bullet that was used in this study. The geometry modelled consisted of the copper jacket and a two-part core made up of steel and lead. The target is a 76.2-mm diameter Al6061-T6 plate, 10.8-mm thick.

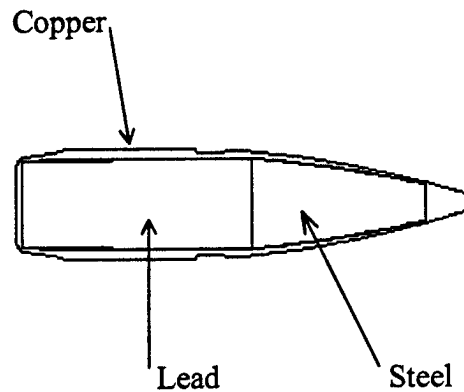


FIGURE 1 - Schematic of the 5.56-mm SS109 bullet

For all the simulations presented, a kinematic/isotropic elastic-plastic hydrodynamic material model was used for both the projectile and target. The model assumes a bi-linear stress-strain behaviour while the strain rate is accounted for very simplistically through a scaling factor applied to the yield stress. The parameters used for both the projectile and target are given in Table I.

TABLE I
Material properties used for LSDYNA2D model

| Parameters | Target | Projectile | | |
|--------------------------------------|-----------|------------|---------|-------|
| | Al-6061T6 | Copper | Lead | Steel |
| Density, ρ (g/cm ³) | 2.768 | 8.96 | 11.35 | 7.82 |
| Yield Strength, σ_y (Mbars) | 0.00335 | 0.0042 | 0.00011 | 0.02 |
| Elastic Modulus, E (Mbars) | 0.7308 | 0.0 | 0.1379 | N/R* |
| Poisson's Ratio, ν | 0.34 | 0.42 | 0.42 | 0.3 |
| Shear Modulus, G (Mbars) | N/R* | 0.447 | N/R* | 0.81 |
| Tangent Modulus, E_t (Mbars) | 0.00646 | 0.0 | 0.0 | 0.02 |
| Failure Strain, f_s | 0.54 | 1.0 | 1.0 | 2.0 |

* N/R = Not Required

Note that the frictional forces between the materials in contact are not modelled. It was assumed that the hydrodynamic pressure dominates the effects of the other forces during the penetration process, and therefore, the frictional forces between the projectile and target are negligible.

3.2 Numerical Mesh

To model the impact, penetration and deformation processes occurring when the projectile impacts the aluminium plate, and the subsequent deformation of both the projectile and the plate, it is necessary to divide the plate and the projectile into a finite number of regions called elements. The network of elements obtained is called a mesh. The material models (i.e. constitutive equations) are then evaluated based on the deformation of the individual elements in the mesh.

Figure 2 shows an example of the initial global finite element mesh that was used for the simulations. This mesh represents the initial state, just as the projectile impacts the target. Due to the axisymmetric nature of the problem studied, only half of the domain needs to be modelled. 4-node quadrilateral elements were used throughout the mesh.

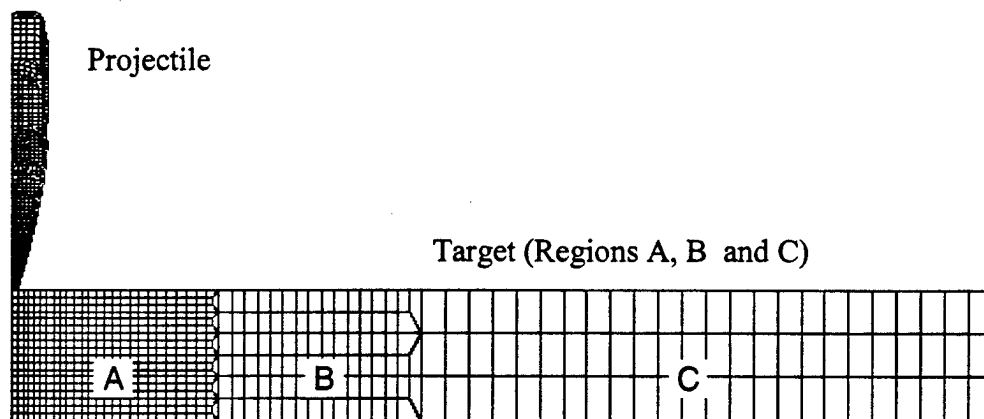


FIGURE 2 -Typical finite element mesh of projectile/target system

As shown in Fig. 2, the target mesh was divided into three regions labelled A, B and C. Numerical simulations have shown that regions B and C do not deform plastically and as a result, could be meshed relatively coarsely. On the other hand, region A experienced large deformation and was therefore meshed more finely. This is necessary to accurately model the contact between the projectile and target elements during the penetration process. Figure 3 shows the three different mesh densities, MD₁, MD₂ and MD₃ that were used for region A to carry out the mesh sensitivity analysis. As also shown in Fig. 3, in all cases the through thickness (t_t as shown in Fig. 3) discretization is the same (i.e. the number of rows of elements used is 18). 18 rows were chosen mainly because as the mesh density approaches its optimum value, the aspect ratios of the elements within the vicinity of the impact region also approach 1.0. Only the mesh density in the plane (horizontally) of the plate was changed. The number of elements, N_{ele} , used in MD₂ was 1.6 times the number of elements in MD₁. Similarly the number of elements used in MD₃ was 1.6 times the number of elements used in MD₂. Table II shows the distribution of the elements within the projectile/target system for the different mesh densities used. The number of elements used to model the target increase as a function of the element increase in region A.

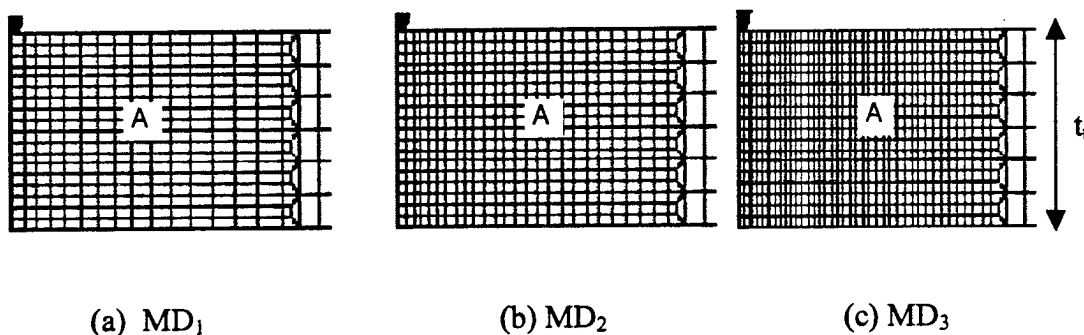


FIGURE 3 - Different mesh densities used in region A of the target. (a) 270 elements (18x15), (b) 450 elements (18x20), (c) 720 elements (18x40)

TABLE II
Element distribution for the various mesh densities

| Mesh Density | Number of Elements | | Total Number of Elements |
|-----------------|--------------------|--------------------------------|--------------------------|
| | Projectile | Target (Region A) ¹ | |
| MD ₁ | 673 | 459 (270) | 1132 |
| MD ₂ | 673 | 639 (450) | 1312 |
| MD ₃ | 673 | 909 (720) | 1582 |

¹ Target is composed of regions A, B and C as shown in Fig. 2. The number of elements in B and C remained constant

3.3 Ballistic Limit Determination

In this study the ballistic limit method was used to investigate the ballistic performance of the various mesh configurations used. The ballistic limit is defined as the minimum striking velocity required to completely perforate a target. This limit is sometimes called the V_{100} limit which, in experimental terms, is the minimum striking velocity at which the projectile will always perforate the target.

The ballistic limit is obtained by first conducting a simulation of the projectile at a striking velocity high enough to completely perforate the target. The residual velocity of the projectile after the target has been perforated is then computed. This procedure is repeated, decreasing the striking velocity until the target is no longer perforated. The striking velocities are then plotted against the corresponding residual velocities. A curve fitting routine is applied to fit the data points to the Lambert/Jonas ballistic equation (Ref. 4) given as

$$V_r = \alpha[(V_s)^p - (V_{100})^p]^{1/p} \quad (1)$$

where V_r and V_s are the projectile residual and striking velocities, respectively. α and p are numerical constants that determine the fit of the equation to numerical data. The striking velocity at which the numerical fit produces a zero residual velocity is then taken as the ballistic limit or V_{100} . This method is described in detail by Zukas (Ref. 4).

4.0 COMPUTATIONAL RESULTS AND DISCUSSIONS

Figure 4 shows a typical example of a simulation that was performed in an effort to obtain the ballistic limit of the 10.8-mm Al6061-T6 target plate against the SS109 5.56-mm bullet. In this case the MD₁ mesh density was used. It can be seen that most of the projectile's copper jacket has eroded and only the deformed back cap remains. The deformed lead section of the core remains behind the steel section which, as expected, did not deform significantly.

Figure 5 shows the variation of the penetrator residual velocity as a function of the initial striking velocity. The results shown here are based on the MD₃ mesh density and a V_{100} of 419 m/s was obtained as the predicted ballistic limit.

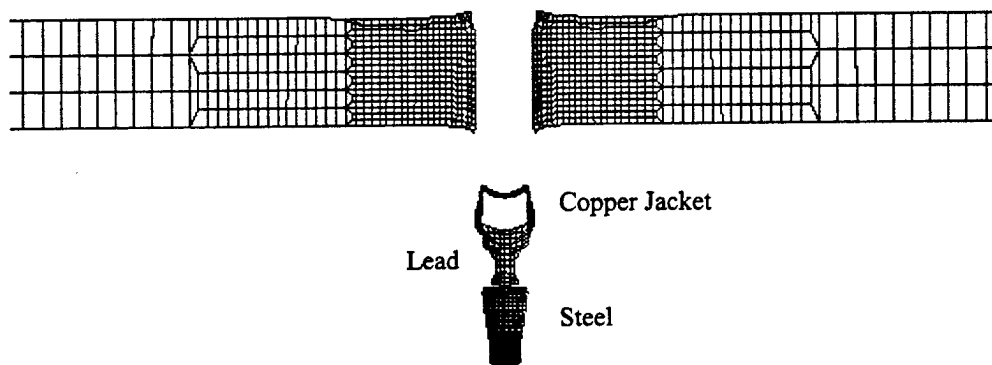


FIGURE 4 - Typical simulation performed to obtain the ballistic limit of the target

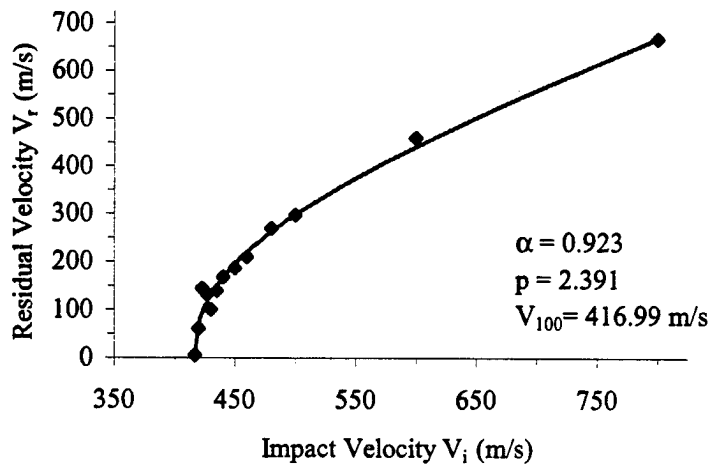


FIGURE 5 -Ballistic limit curve for 10.8-mm Al-6061T6 aluminium plate for which the mesh density in region A is given by MD₃.

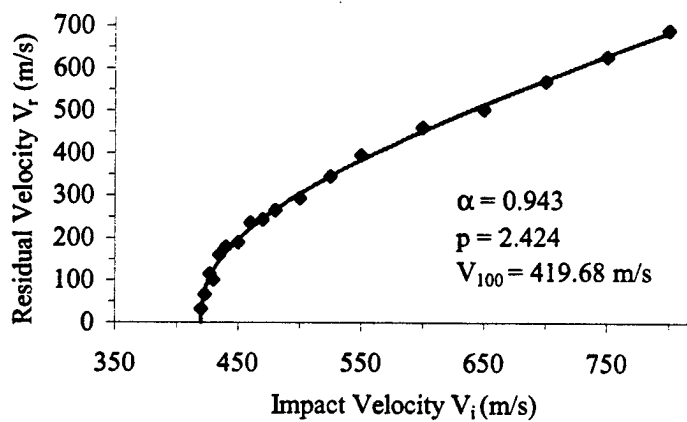


FIGURE 6 - Ballistic limit curve for a 10.8-mm Al-6061T6 aluminium plate for which the mesh density in region A is given by MD₂.

Figures 6 and 7 show the variation of the penetrator residual velocity as a function of the initial striking velocity for the MD₂ and MD₁ cases respectively. The MD₂ mesh gives a V_{100} of 417 m/s whereas for the MD₁ case the V_{100} was 394 m/s.

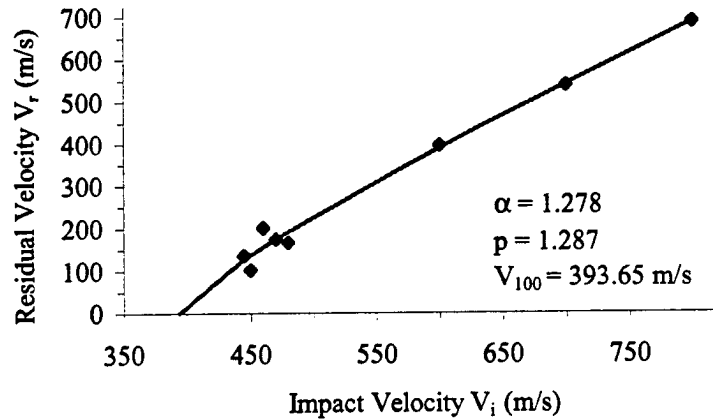


FIGURE 7 - Ballistic limit curve for a 10.8-mm Al-6061T6 aluminium plate for which the mesh density in region A is given by MD₁.

Table III gives a summary of the target ballistic limits for the different mesh densities shown in Fig. 3. It can be observed that as the mesh density increases in the impact region the ballistic limit converges. It can be seen that increasing the number of elements in the target from 639 (MD₂) to 909 (MD₃) translates into a 2 m/s change in the ballistic limit. However, increasing the mesh density from MD₁ to MD₂ changes the ballistic limit by 23 m/s. These results suggest that MD₂ could be used as the optimum mesh density for the impact region.

TABLE III
Ballistic limits obtained for different target region A mesh densities

| Mesh Density Type | Ballistic Limit (m/s) |
|--------------------------|------------------------------|
| MD ₁ | 394 |
| MD ₂ | 417 |
| MD ₃ | 419 |

Figure 8 shows the relative CPU time needed to run each of the mesh densities analysed. A common impact velocity was used for all the mesh densities in order to compare the CPU time. The relative CPU time shown in Fig. 8 is the actual CPU time taken for each simulation to complete, normalized to the smallest CPU time obtained, (i.e. that of the MD₂ run). The results in Fig. 8 show that as the mesh density increases the CPU time also increases for mesh densities that are larger than the optimised mesh density. However, the smallest mesh density, MD₁, also has a larger relative CPU time than the optimised MD₂ mesh density. This suggests that if the element size within the impact region is too large then phenomena such as hourglassing and other associated instabilities can cause the time step to get smaller thereby increasing the CPU run time. Although there may be other important factors involved, numerous simulations of this impact problem indicate that an optimum mesh density is required before any realistic hydrocode simulations can be conducted.

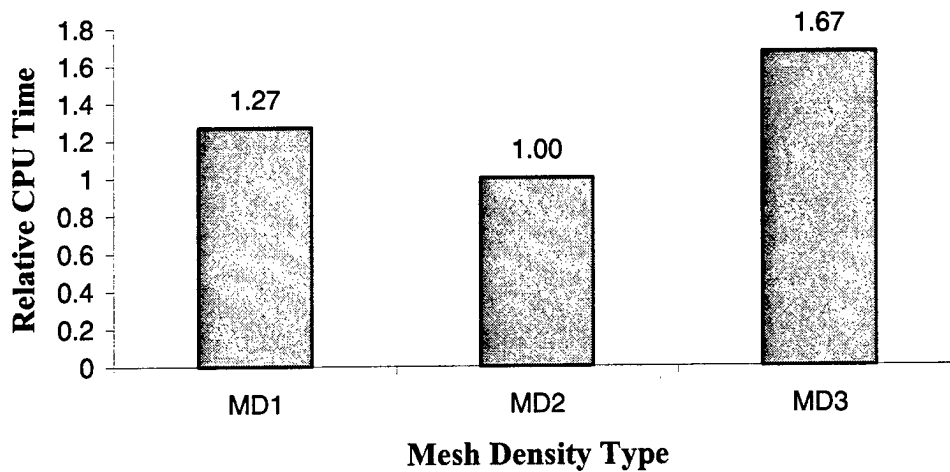


FIGURE 8 - Comparison of CPU run time, normalised to the MD₂ result, for the different mesh densities used in region A of the target mesh.

5.0 CONCLUSIONS

This study examined the effect of the mesh density on the prediction of the ballistic limit of a 10.8-mm thick 6061-T6 aluminium plate struck by a 5.56-mm SS109 bullet. Numerous simulations of the impact problem were conducted using three different mesh densities in the impact zone of the target.

The ballistic limit of the target plate was obtained for each of the three mesh densities. The results obtained show that an optimised finite element mesh in the impact region will yield consistent results. An optimised mesh density was defined as the minimum number of elements required to conduct realistic simulations without significantly changing the predicted ballistic response if the number of elements is increased. It was shown that as the number of elements is increased above the optimised mesh density, the run time increases significantly with little improvement in the accuracy of the ballistic limit. On the other hand, if the number of elements is decreased below the optimised mesh density, both the run time and the error in the accuracy of the predicted ballistic limit could increase substantially.

Finally, given the current status of hydrocode modelling, it was concluded that an optimisation of finite element mesh in the impact region of the target must be performed before any parametric studies can be conducted.

6.0 ACKNOWLEDGEMENTS

Special thanks are addressed to Dr. Kevin Williams and Mr. Alfred Jeffrey for their comments and the review of this document.

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This memorandum presents the study to examine the effect of the mesh density on the ballistic limit determination of a 1.08-cm thick 6061-T6 aluminium plate struck by a 5.56-mm SS109 bullet.

The ballistic limits of the target plate were obtained for three different mesh densities. The results showed that an optimised finite element mesh in the impact region would yield consistent penetration results. It was also shown that as the number of elements is increased, the CPU run time increases significantly but with little gain in the accuracy of the ballistic limit. On the other hand, if the number of elements is decreased below the optimised mesh density, the CPU time could increase significantly and errors in the accuracy of the predicted ballistic limit could be large due to hourglassing and severe mesh distortion.

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